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Original Article

Study of absorbed dose in important organs during helical CT chest scan using MCNP code and MIRD phantom

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ABSTRACT

Purpose: Study of absorbed dose in the heart, breast, stomach, lungs, thyroid, kidney, and liver during CT scan of the chest at different tube voltages using Medical Internal Radiation Dose (MIRD) phantom and MCNP code at values of tube voltage 80 kVp, 100 kVp, and 120 kVp.

Method: The graphical interface, CT-DOSE CALC, was based on Visual Basic language and linked to a Monte Carlo code in order to simulate the movement of radiation source in both types of computed tomography imaging (axial/helical scan). The modified ORNL MIRD phantom was used to evaluate the average deposited energy and absorbed dose in important organs and tissues. Also the absorbed dose in heart, skin, and the ratio between the absorbed dose in skin and the absorbed dose in heart were calculated.

Results: The absorbed doses in heart muscle were 9.11, 21.86, 36.99 mGy, in breasts were 2.03, 3.90, 6.22 mGy, and for thyroid were 0.78, 1.66, 2.79 mGy at 80, 100, 120 kVp respectively.

Conclusion: As a result of CT chest scan, it is always necessary to set accuracy to obtain acceptable images for medical diagnosis and to reduce patient dose to minimum.

1. Introduction

Radiation dose from computed tomography (CT) has become a public concern. With the increasing use of CT, the radiation exposure from CT scans has become the primary contributor to the public medical exposure. According to National Council on Radiation Protection and Measurements (NCRP) report No. 160, CT scans contributed half of the total patient medical exposure [1]. Effective dose resulting from the computerized imaging devices extends within the range of 1–12 mSv. The effective dose at tomography of the abdomen and pelvis is about 10 mSv and it is higher than the amount of 400–500 times the dose caused by conventional imaging of the chest, estimated at 0.02–0.04 mSv. On the other hand, the dangers arising from this radiation have random effect that does not appear immediately, but may appear in later years or even generations later [2].

Table 1 gives a comparison between the effective dose resulting from the computed tomography and each of the traditional imaging of the chest and the number of years of exposure to natural background radiation which produces the same effective dose resulting from computed tomography [2].

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Table 1
A comparison between the effective dose resulting from the computed tomography and each of the traditional imaging of the chest and the number of years of exposure to natural background radiation which produces the same effective dose resulting from computed tomography.

Imaging protocol	Effective dose (mSv)	Number of the chest's images in the traditional imaging	Number of years of exposure to natural background radiation
Head scan	2.3	115	1 year
Chest scan	8	400	3.6 year
Abdomen and pelvis scan	10	500	4.5 year

1.1. MCNP code

MCNP is comprised of about 425 subroutines written in Fortran 90 and C. MCNP has been made as system independent as possible to enhance its portability, and has been written to comply with the ANSI Fortran 90 standard.

MCNP is a general-purpose Monte Carlo N–Particle code (MCNP) that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport, including the capability to calculate given values for critical systems. For photons, the code accounts for incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung [3].

Table 2
Elemental composition of the tissues for all phantoms except the newborn [6].

Element	Percent by weight		
	Lung	Skeleton	Soft tissue
H	10.134	7.337	10.454
C	10.238	25.475	22.663
N	2.866	3.057	2.490
O	75.752	47.893	63.525
F	0	0.025	0
Na	0.184	0.236	0.112
Mg	0.007	0.112	0.013
Si	0.006	0.002	0.030
P	0.080	5.095	0.134
S	0.225	0.173	0.204
Cl	0.266	0.143	0.133
K	0.194	0.153	0.208
Ca	0.009	10.190	0.024
Fe	0.037	0.008	0.005
Zn	0.001	0.005	0.003
Rb	0.001	0.002	0.001
Sr	0	0.003	0
Zr	0	0	0.001
Pb	0	0.001	0
Density	0.296 g/cm^3	1.4 g/cm^3	1.04 g/cm^3

1.2. Visual basic

Visual Basic is a tool that allows you to develop Windows (Graphic User Interface - GUI) applications. The applications have a familiar appearance to the user.

Visual Basic is event-driven, meaning code remains idle until called upon to respond to some event (button pressing, menu selection, ...). Visual Basic is governed by an event processor [4].

1.3. Computational phantom

The computational phantom, designed to represent human anatomy, started with a simple geometry of cylinders and spheres of homogeneous composition. The first

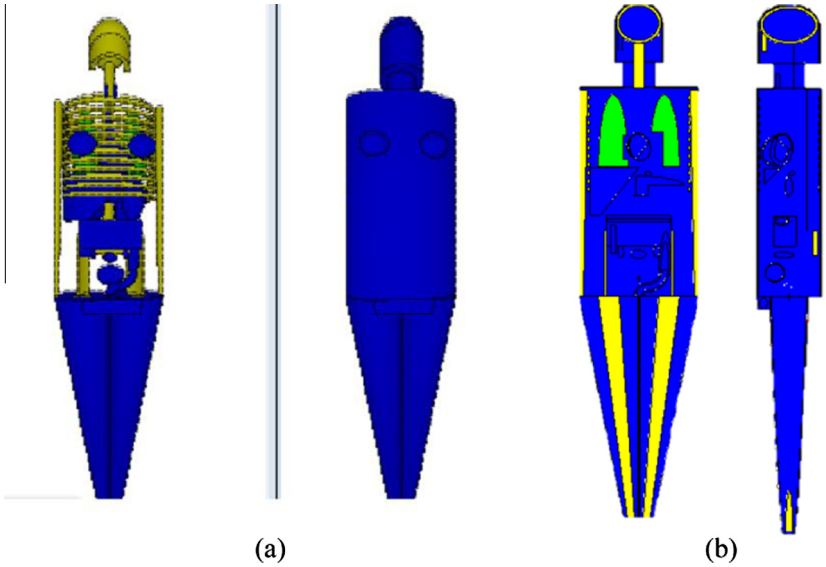

Fig. 1. The mathematical Phantom adopted in this research using MCNP5-beta code, (a) three-dimension drawing, (b) two-dimensional drawing.

heterogeneous model was introduced by Fisher and Snyder of Oak Ridge National Laboratory (ORNL) for Medical Internal Radiation Dose (MIRD) [5] in the 1970s using the anatomical data of the "Reference Man" publication of the International Commission on Radiological Protection (ICRP). Reference Man is defined as a Western European or North American adult male of 170 cm in height, weighing 70 kg, and 20–30 years of age [5]. The computational phantom has gone through continuous revisions since its initial development. Based on the early MIRD model which was an adult hermaphrodite model with gender-specific organs, ORNL had developed not only a series of age-specific models but also pregnant female models at different stages of pregnancy [5]. And GSF (National Research Center for Environment and Health, Germany) developed gender-specific adult models, known as ADAM and EVA, based on the original MIRD model [5].

As the MIRD model has been a standard for computational dose assessment for internal and external exposures to radiation, many organizations including the Nuclear Regulatory Commission (NRC) have used it. The phantom model currently used by the NRC is the MIRD-5 phantom, published in 1974, and this model developed MCNP code [5].

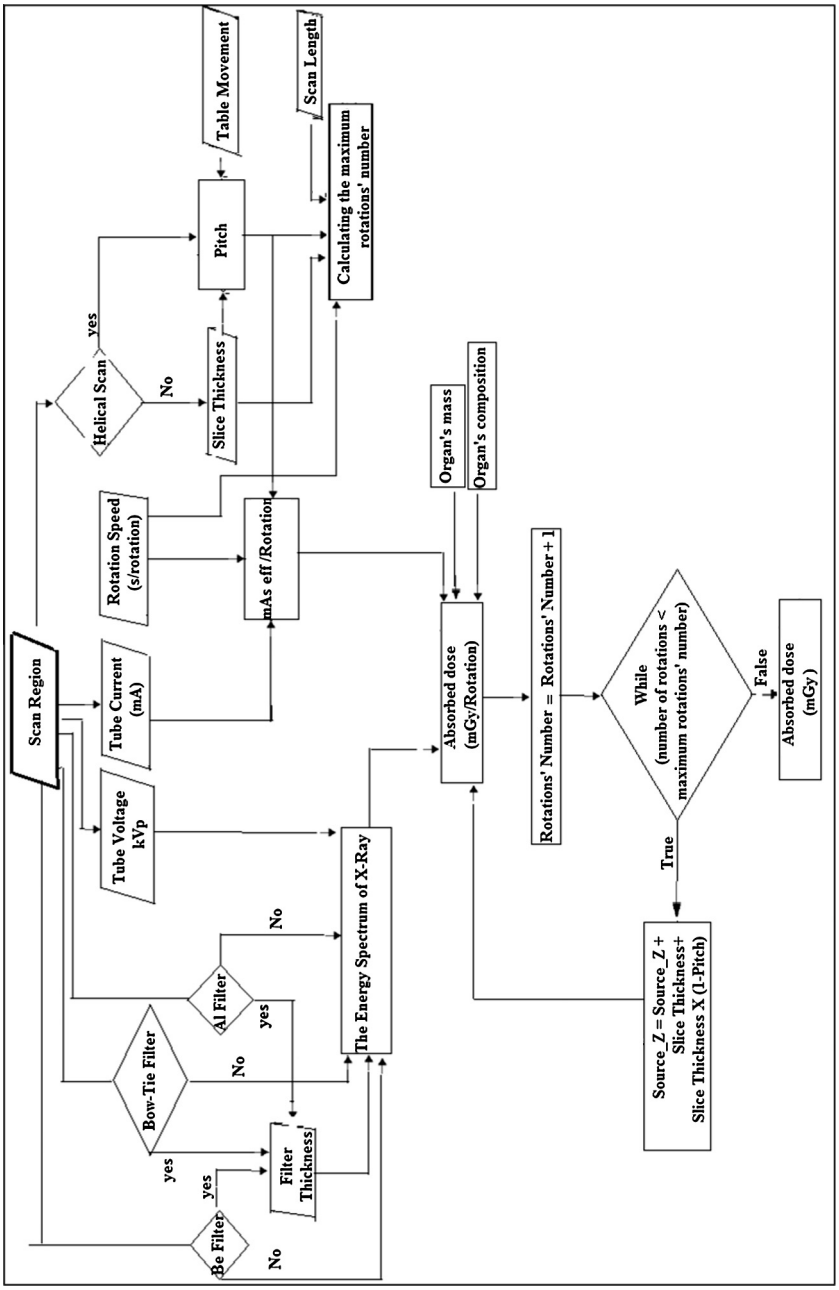

Fig. 2. Flowchart of CT-DOSE CALC program.

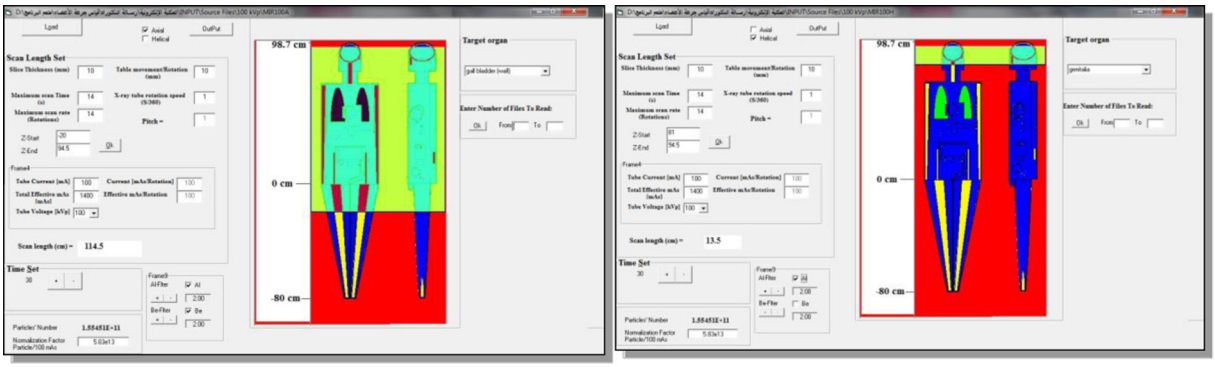

Fig. 3. User interface of CT-DOSE CALC program.

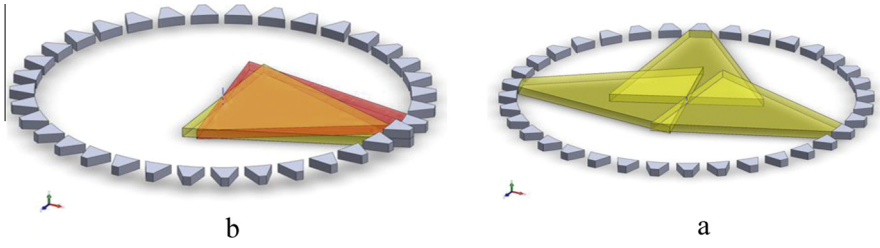

Fig. 4. The adopted design for X-ray source to cover each rotation in both scan types: (a) axial and (b) helical scan.

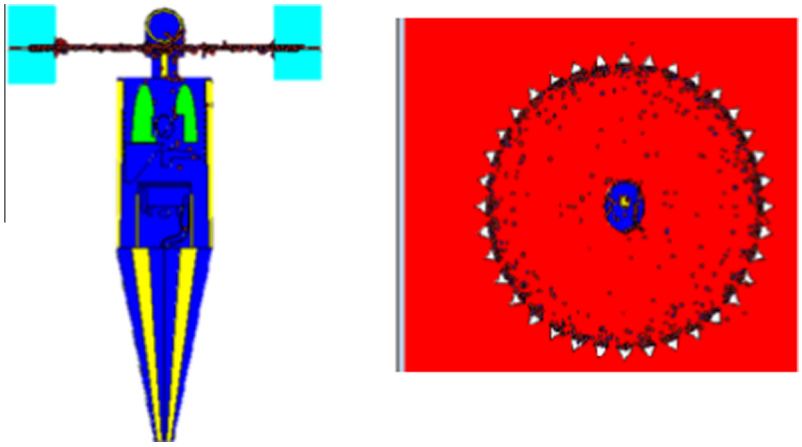

Fig. 5. The distribution of X-ray photons within the phantom after one rotation using MCNP5 code-Beta.

Table 3
Comparison between the values of normalization factor that were calculated using MCNP code and some given studies.

Voltage kVp	Normalization factor (particle/100 mAs)	Normalization factor (particle/mAs)		Relative error
	Ref. [8]	Ref. [7]	In this work slice thickness = 10 mm	
80	4.18×10^{13}	2.53×10^{11}	3.66×10^{11}	0.0233
100	5.83×10^{13}	3.96×10^{11}	4.50×10^{11}	0.0235
120	7.65×10^{13}	4.12×10^{11}	5.37×10^{11}	0.0228
140	9.50×10^{13}	–	6.48×10^{11}	0.0234

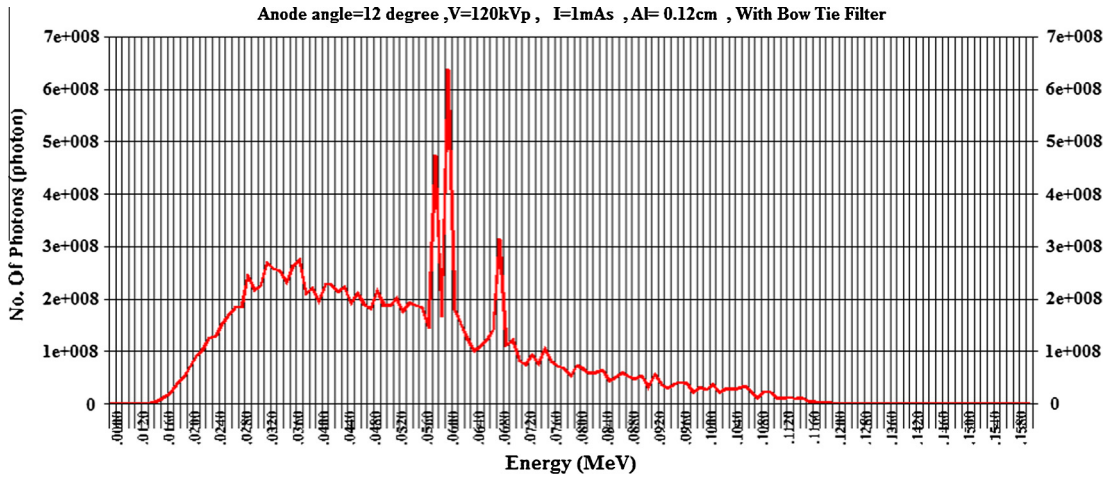

Fig. 6. Energy spectrum of photons produced at 120 kVp on tungsten target using MCNP code.

Table 4
Helical CT-chest scan parameters used in study.

Parameter	Value
Table movement	12 mm
Slice thickness	10 mm
Pitch[a]	1.20
Tube voltage	80 kVp, 100 kVp, 120 kVp
Tube current	240 mA
Effective mAs[a]	200 mAs
Scan length	40–70 cm
Al filter	10 mm
Time	500 min

[a] These values are calculated in the program.

In this study, the Reference Phantom ORNL MIRD, 1996 version, was simulated. The phantom contains female organs (ovary, uterus, breast) as well as male organs. Three different areas of density can be distinguished in this phantom: skeleton, soft tissue, and lung (Table 2).

2. Purposes of the research

To study the absorbed dose in the heart, breast, stomach, lungs, thyroid, kidney, and liver during CT scan of the chest at different tube voltages using Medical Internal Radiation Dose (MIRD) phantom and MCNP code.

3. Methods and materials

Because of difficulty in simulating X-ray source movement in a helical CT scan using MCNP code, an assistant

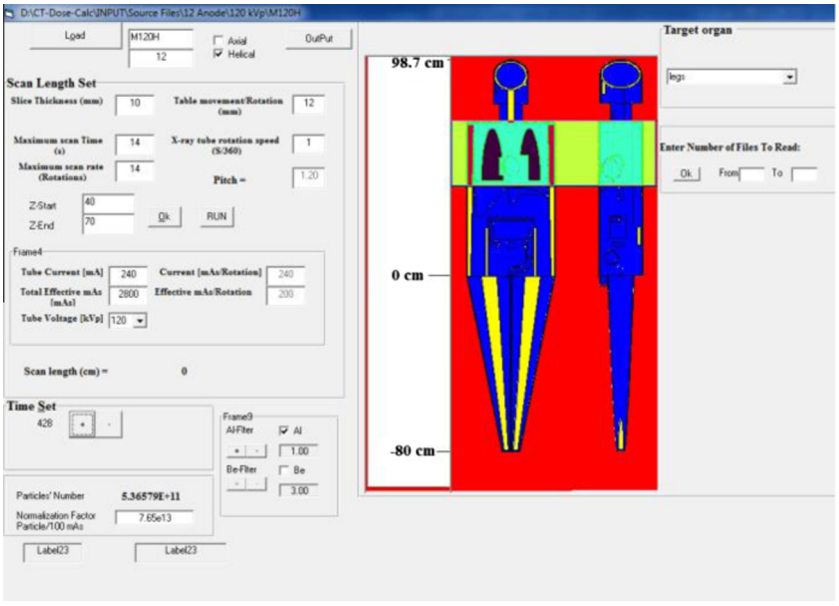

Fig. 7. The scanned region is shown on MIRD phantom during CT chest scan.

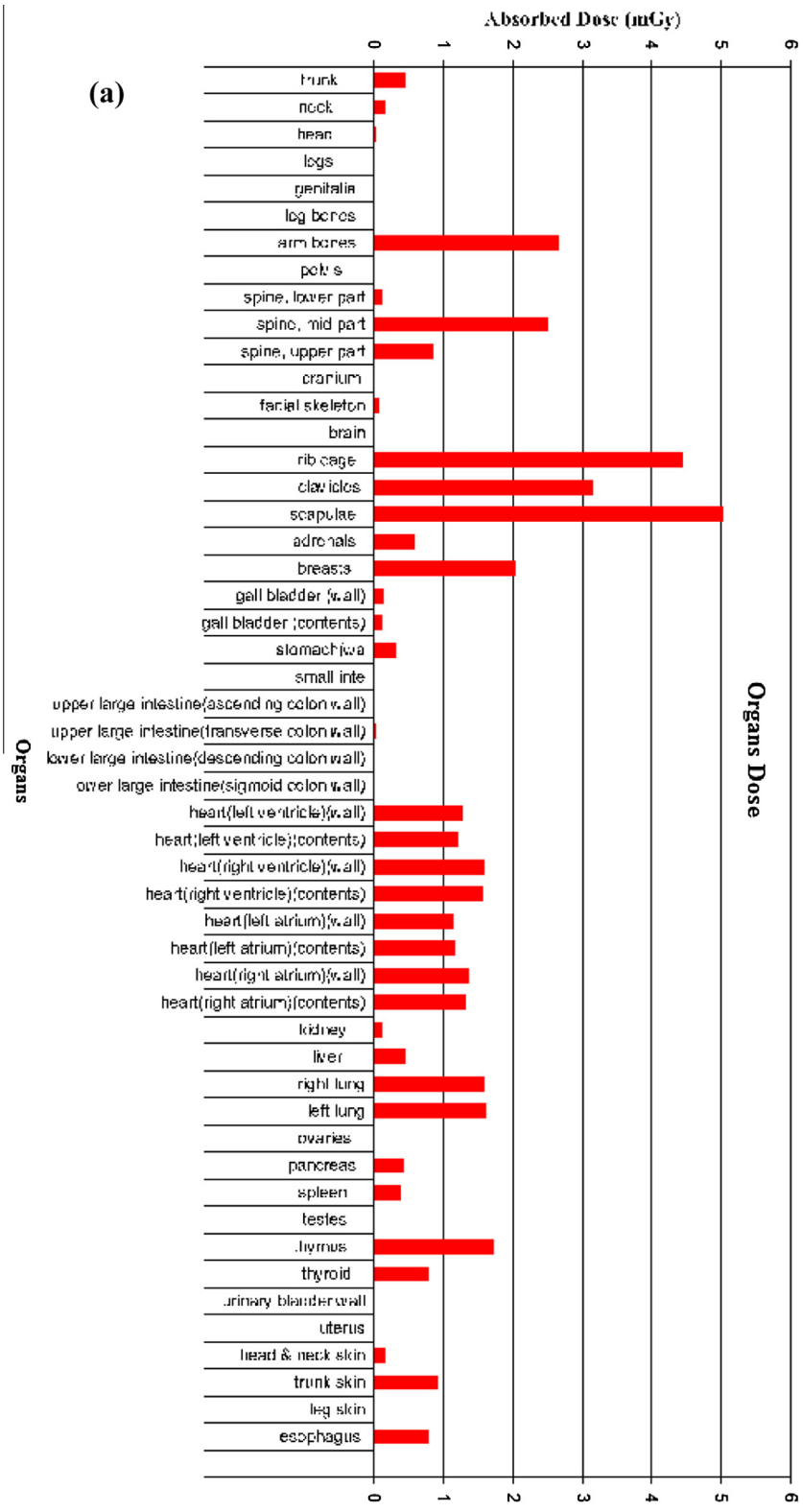

Fig. 8. Absorbed dose distribution in organs for different tube voltages: (a) 80 kVp, (b) 100 kVp, (c) 120 kVp.

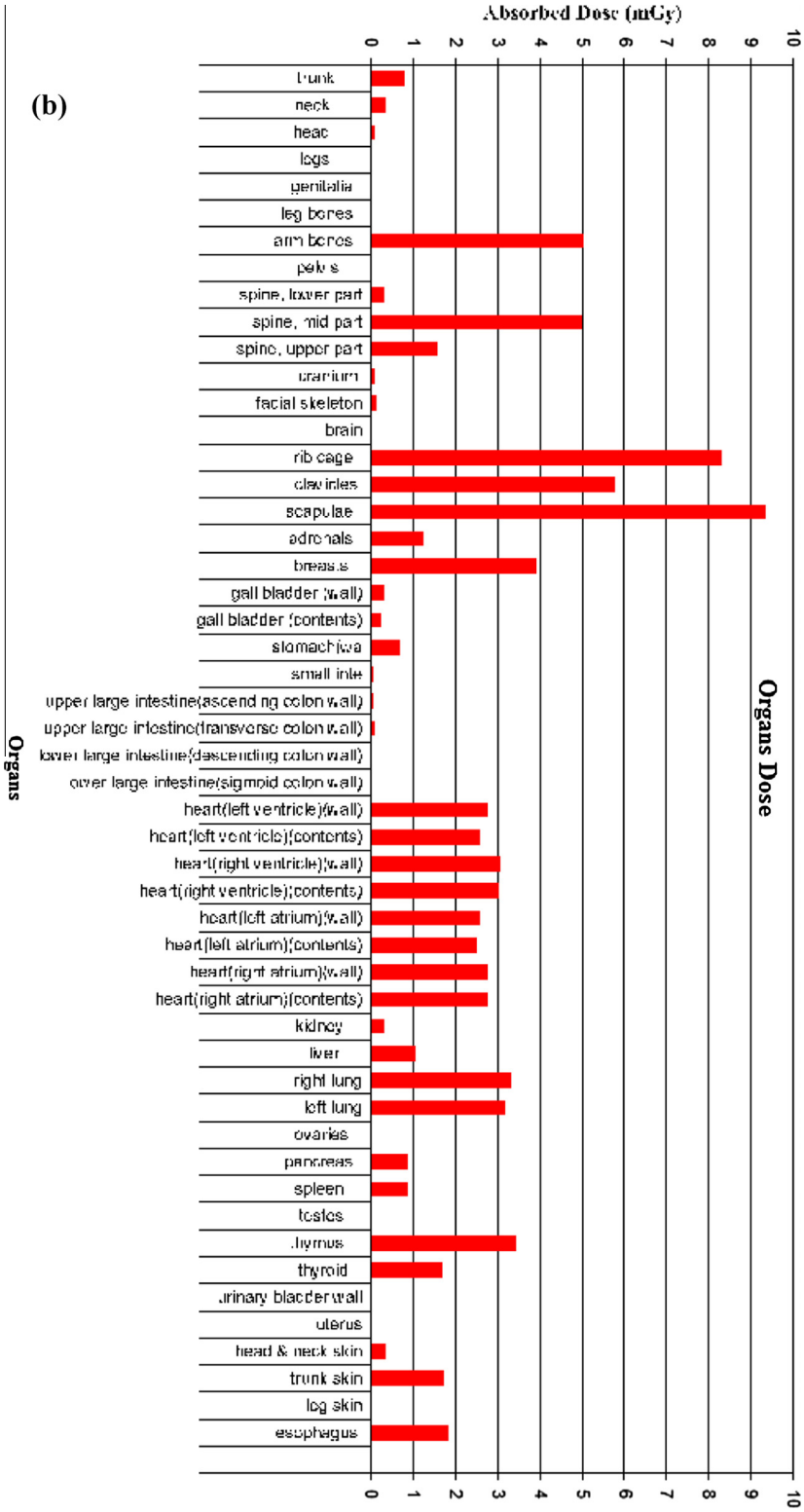

Fig. 8 (*continued*)

program (CT-DOSE CALC Program) was designed using Visual Basic programming language which plays a role in link between user (via a visual interface that contains the boxes, drop-down lists, buttons and others to help the

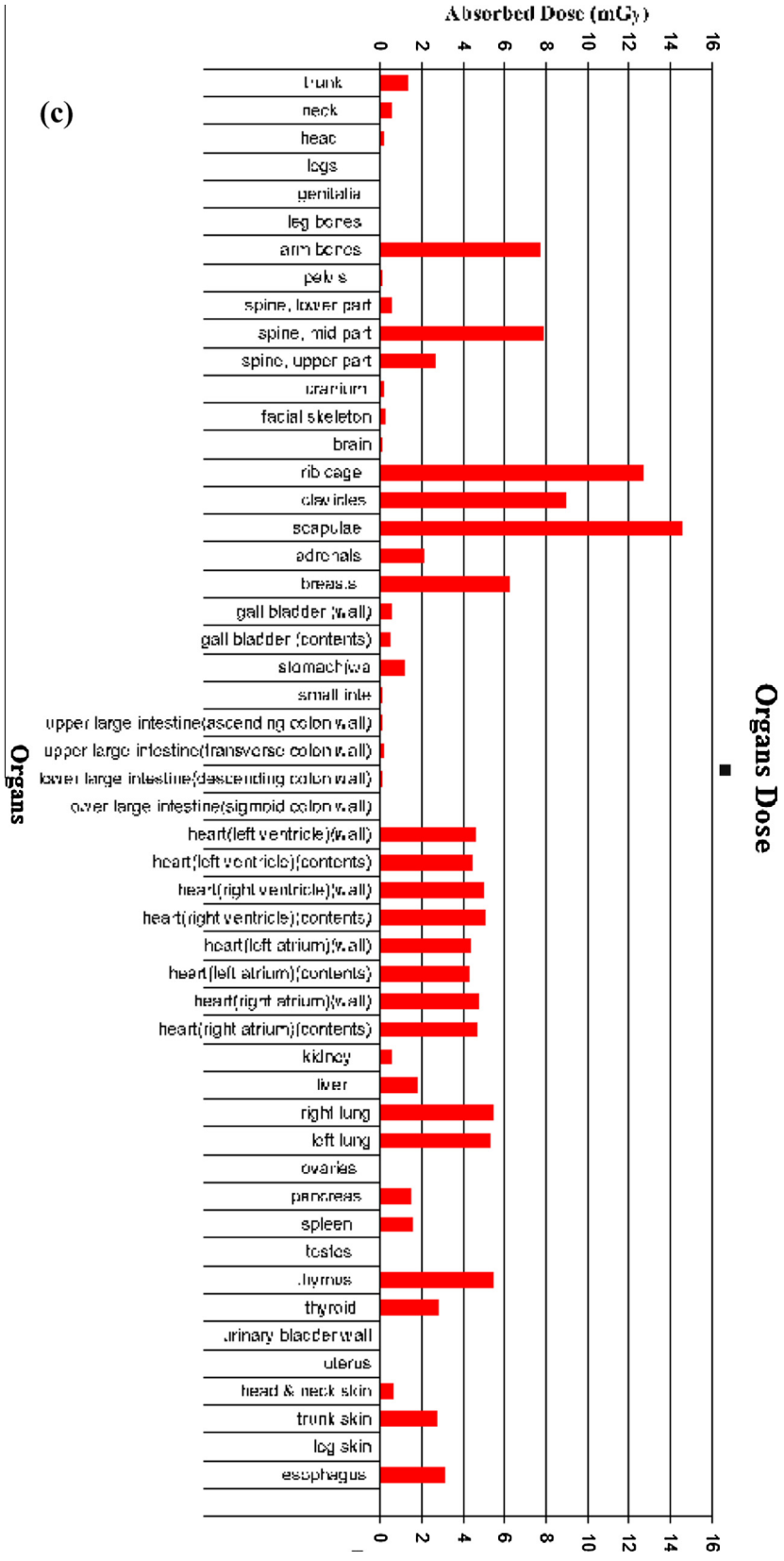

Fig. 8 (*continued*)

user) and the MCNP code to, simulate the X-ray tube motion in both types of imaging (helical and axial scan), and evaluate the energy spectrum of the X-ray tube in a computed tomography. The program was used to evaluate the values of absorbed doses in important organs inside body versus scan parameters (tube voltage, exposure current-time product (mAs), filter thickness, pitch, scan length and number of rotations).

Therefore, the MIRD phantom (Fig. 1) was used to simulate the human body anatomy and evaluate the absorbed dose values.

3.1. CT-DOSE CALC program

A graphical interface program was built (so-called CT-DOSE CALC), using visual basic 6.0 language. This program allows user to enter the scan parameters for each scan protocol, after that, the program will create the corresponding MCNP input file. After run termination, the output files would be processed by the program to obtain the desired results and display it, on its graphical interface, the values of absorbed dose in each organ in (mGy), or schemes.

The CT-DOSE CALC program works on Windows XP or Windows 7. The minimum specifications are approximately 2.5 GB of hard drive (including MCNP code) and 512 MB of RAM. Fig. 2 shows the flowchart of CT-DOSE CALC program, and Fig. 3 shows the user interface.

3.1.1. X-ray source simulation

3.1.1.1. Axial scan. Each rotation of X-ray tube was divided into thirty-five surface sources distributed on the circumference of a circle and separated by equal angles (10°). The sources were simulated using the "Transformation (TR)" feature available in the code MCNP. The distance between the source and center (Source Iso-center Distance, SID) equals 60 cm, and fan beam angle of 42.5° was adopted, but the thickness of the slice and the scan length can be changed by the user.

3.1.1.2. Helical scan. In this case, the source moves in circular path about the center (about Oz-axis), also patient's table moves toward front (in Oz-axis) then the pitch can be defined as the table travel per rotation divided by the collimation of the X-ray beam for helical CT scans [1].

Some approximation methods were found to simulate the source motion in helical scan. Each pitch of X-ray tube was divided into thirty-six surface sources distributed according to a helical path and separated by equal angles (10°). Fixed distance between the source and center (Source Iso-center Distance SID = 60 cm) and the Fan Beam angle = 42.5° were adopted, but the thickness of the slice, the scan length, and pitch can be changed by the user. Fig. 4 shows the adopted design for X-ray source to cover each rotation in both scan types (axial and helical scan). Fig. 5 represents the phantom during the simulation of CT scan and it shows the distribution of X-ray photons after one rotation.

4. Calculation of organs' dose using MCNP code

In order to evaluate the deposited energy in each cell (MeV/g), the F6 tally card was used. F6 can be represented as follows:

$$F_6 = W \cdot T_l \cdot \sigma_T(E) \cdot H(E) \cdot \frac{\rho_a}{m} \quad (1)$$

where W: particle weight; T_l: rack length (cm); $\sigma_T(E)$: microscopic total cross section (barns); H(E): eating number (MeV/collision); ρ_a: tom density (atoms/barn-cm); m: cell mass (g).

The results of F6 tally were multiplied by (1.6×10^{-10} (J/kg)/(MeV/g)) in order to convert it into (Gy). To get the deposited energy for one tube rotation, it is necessary to multiply the final value by effective current-time product (eff mAs), and then the produced dose value during single rotation for single organ is added to another value that is produced from the next rotation for the same organ; finally, we will get the total dose (Gy) for each organ. All

Table 5
Absorbed dose in the heart muscle parts, breasts, stomach wall, thyroid, kidney, and lungs at 80, 100, 120 kVp.

Part name		Volume cm^3	Maximum absorbed dose mGy		
			80 kVp	100 kVp	120 kVp
Heart muscle	Heart (left ventricle wall)	177	1.27	2.73	4.57
	Heart (left ventricle contents)	102	1.20	2.57	4.45
	Heart (right ventricle wall)	67.02	0.78	3.04	5.00
	Heart (right ventricle contents)	108	1.55	2.99	5.01
	Heart (left atrium wall)	31.6	1.14	2.54	4.30
	Heart (left atrium contents)	115	1.16	2.48	4.25
	Heart (right atrium wall)	27.4	0.65	2.75	4.73
	Heart (right atrium contents)	111	1.36	2.76	4.68
	Sum		**9.11**	**21.86**	**36.99**
Breasts		337.0	2.03	3.90	6.22
Stomach wall		152.0	0.30	0.67	1.16
Thyroid		19.9	0.78	1.66	2.79
Kidney		288.0	0.10	0.28	0.52
Liver		1830.0	0.45	1.02	1.75
Right lung		1810.0	1.58	3.29	5.45
Left lung		1560.0	1.60	3.16	5.28

these operations are done automatically by the program. However, the results of MCNP5 are given per source particle; therefore, a normalization factor should be used. In this study, the normalization factor represents the total number of X-ray photons per current-time product unit (Photon/mAs). Table 3 shows a comparison between the values of normalization factor calculated in this study with those from previously published studies. The relative error for all calculated values was less than 5%.

It should be noted that the tally card F6 represents the average deposited energy on the entire energy spectrum of particles. For the tungsten target, the energy spectrum is ranged between 0 and 140 keV at tube voltage 120 kVp, Fig. 6 [9].

5. Study of absorbed dose in organs in helical CT chest scan

In order to evaluate the absorbed dose in important organs during CT chest scan, the program was run using the parameters shown in Table 4. Fig. 7 shows, on the GUI of program, the scanned region of MIRD phantom.

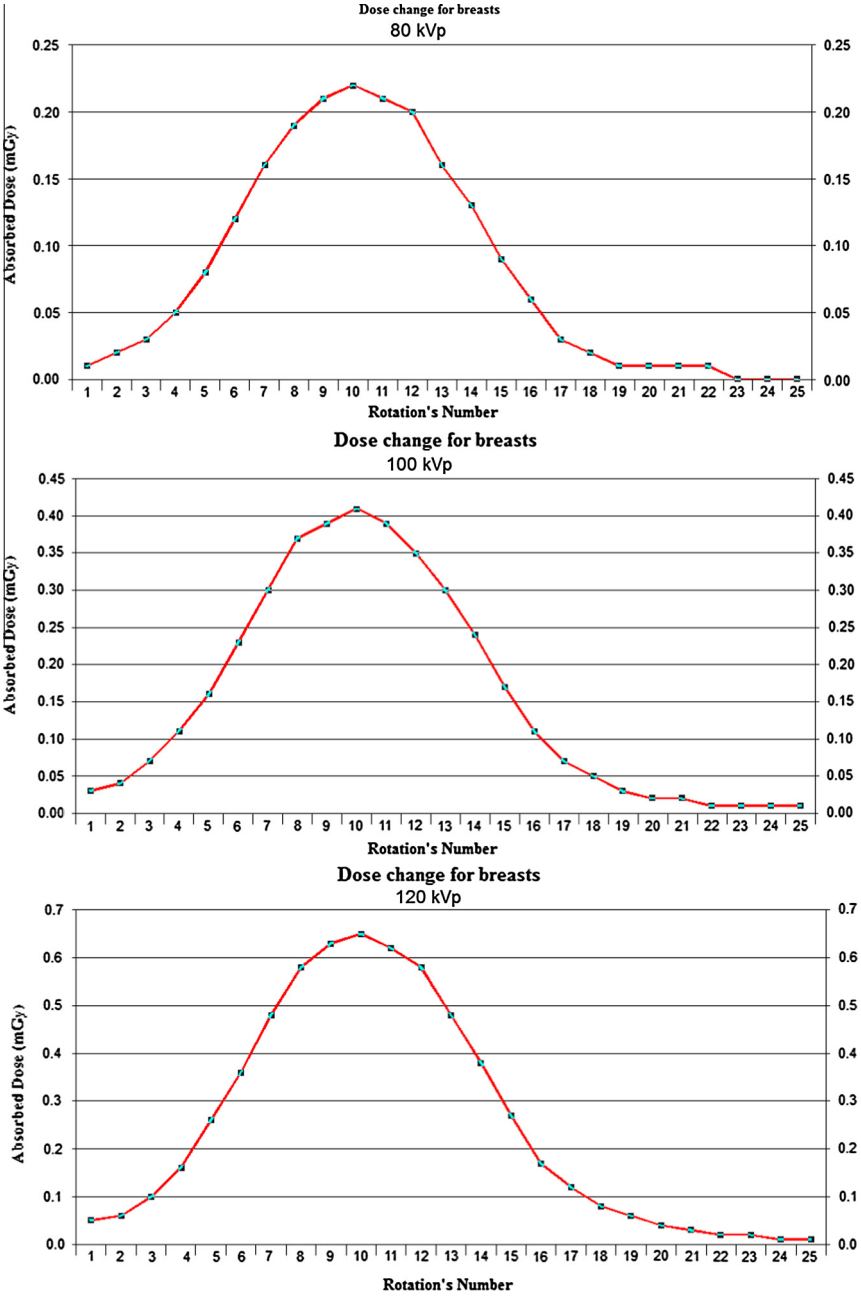

Fig. 9. The distribution of the absorbed dose in the breast during scan process at 80, 100, 120 kVp.

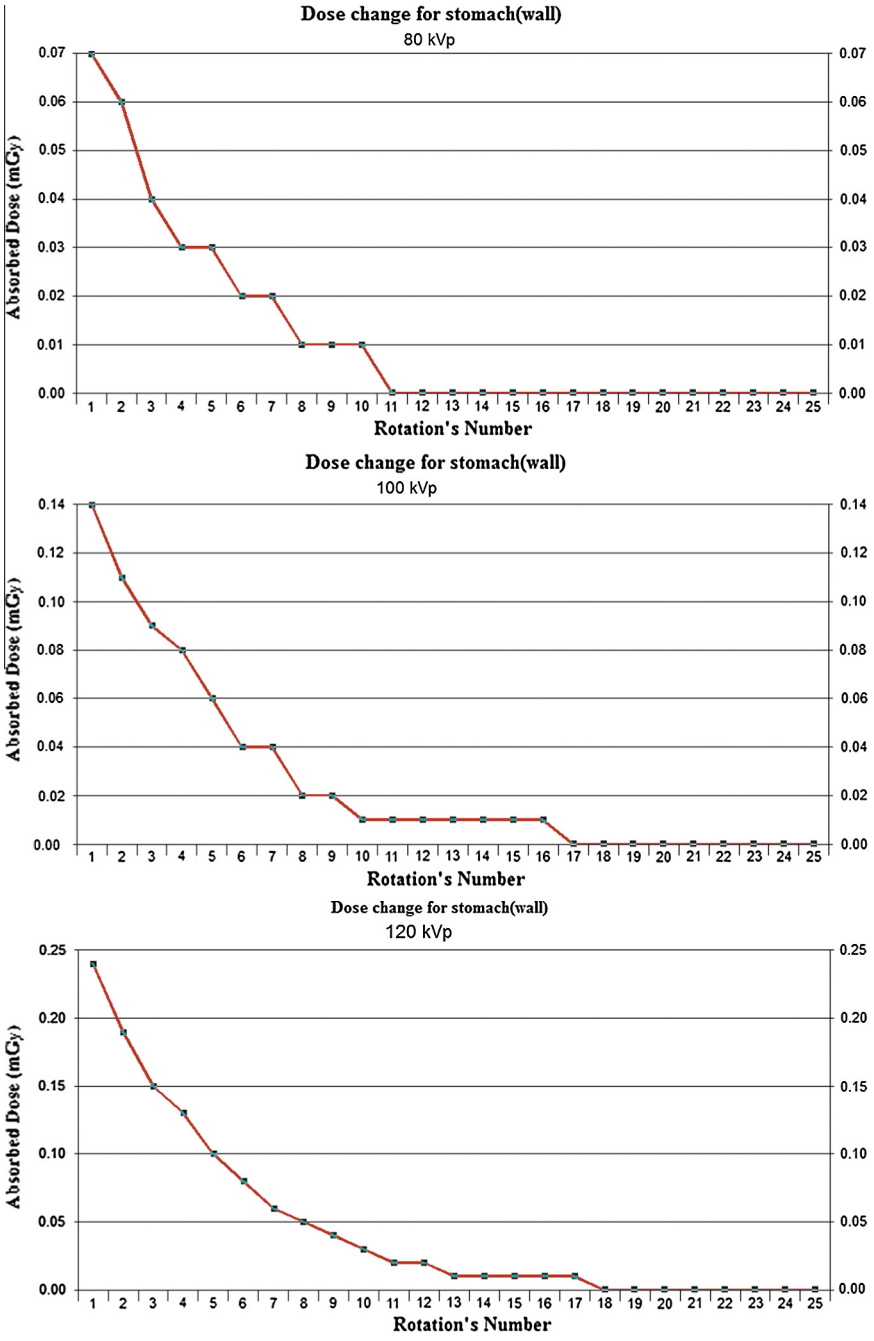

Fig. 10. The distribution of the absorbed dose in stomach wall during scan process at 80, 100, 120 kVp.

Using the abovementioned parameters, Table 4, the CT-DOSE CALC program gives the results as histograms (Fig. 8) and numerical values (Table 5).

Figs. 9–11 show the absorbed dose in breasts, stomach wall, and thyroid, at 80, 100, 120 kVp, during CT chest scan, as a function of rotation number using the same previous parameters (Table 4).

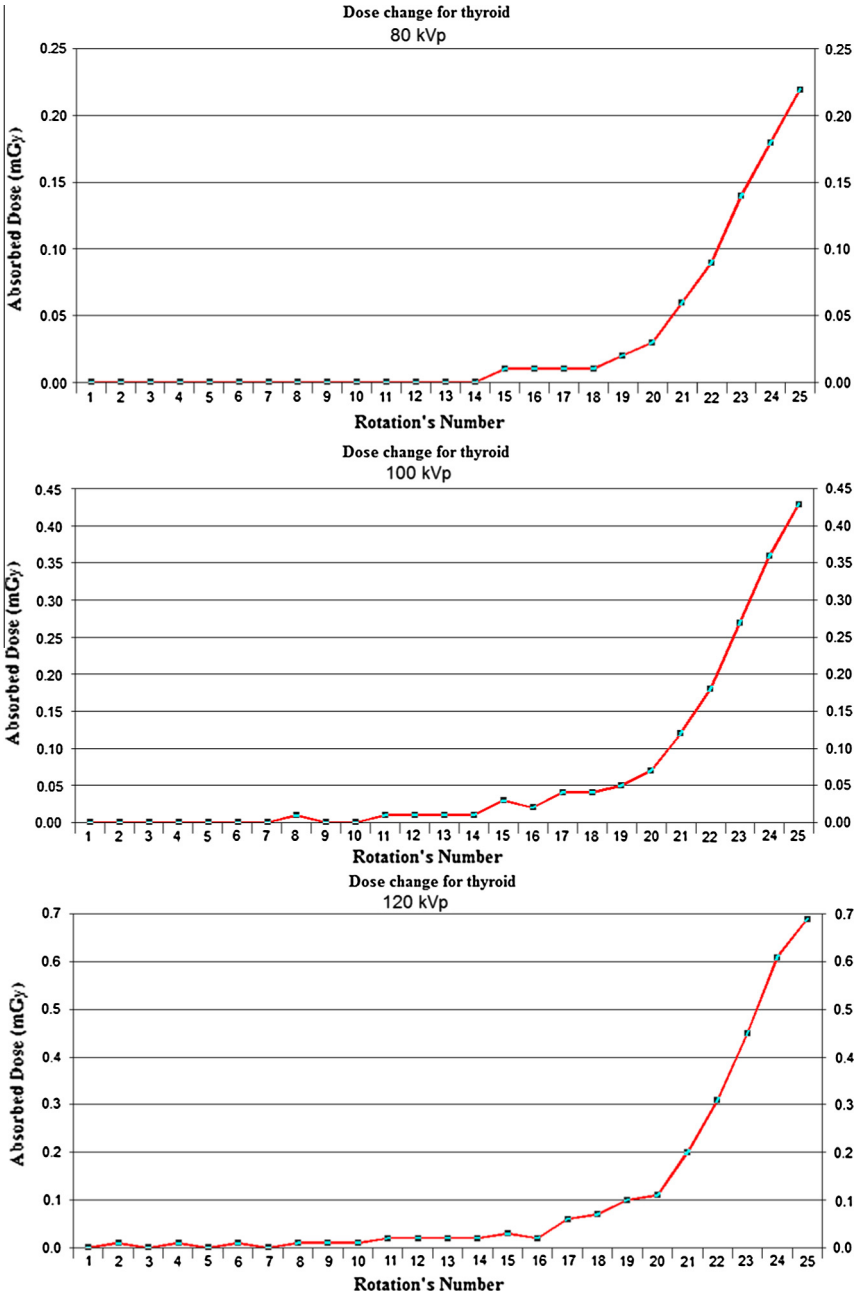

Fig. 11. The distribution of the absorbed dose in thyroid during scan process at 80, 100, 120 kVp.

6. The effect of tube voltage on the absorbed dose in organs during CT chest scan

Table 6 gives the effect of tube voltage value on the absorbed dose in the heart, breast, esophagus for CT chest scan when the other parameters are constants. Fig. 12 represents the absorbed dose in heart, skin versus tube voltage in this study, and Table 7 represents the absorbed dose in heart, skin, and the ratio between the absorbed dose in skin and the absorbed dose in heart.

7. Discussion

In case of breasts, Fig. 9, the maximum values of dose were at the middle of scan, and these values were 0.23, 0.40, 0.63 mGy at 80, 100, 120 kVp, respectively. Stomach wall, Fig. 10, will receive the maximum values of dose at the beginning of scan, and these values were 0.07, 0.14, 0.24 mGy at 80, 100, 120 kVp, respectively. For thyroid, Fig. 11, the maximum values of dose were at the end of

Table 6
The effect of tube voltage value on the absorbed dose in the heart, breasts, esophagus, kidney, thyroid, and stomach(wall) for CT chest scan.

	Voltage = 120 kVp Absorbed dose mGy	Voltage = 100 kVp Absorbed dose mGy	Percent deviation % Dose (100 kVp) * 100/Dose (120 kVp)
Heart(left ventricle)(wall)	4.57	2.73	59.74%
Heart(left ventricle)(contents)	4.45	2.57	57.75%
Heart(right ventricle)(wall)	5.00	3.04	60.80%
Heart(right ventricle)(contents)	5.01	2.99	59.68%
Heart(left atrium)(wall)	4.30	2.54	59.07%
Heart(left atrium)(contents)	4.25	2.48	58.35%
Heart(right atrium)(wall)	4.73	2.75	58.14%
Heart(right atrium)(contents)	4.68	2.76	58.97%
Breasts	6.22	3.90	62.70%
Esophagus	3.11	1.83	58.84%
Kidney	0.52	0.28	53.85%
Thyroid	2.79	1.66	59.50%
Stomach(wall)	1.16	0.67	57.76%

Table 7
Absorbed dose in heart, skin, and the ratio between the absorbed dose in skin and the absorbed dose in heart.

X (kVp)	D(Heart)	D(Skin)	D(Skin)/D(Heart)
68	0.349	0.3687	1.06
69	1.046	0.424	0.41
70	1.743	0.4793	0.27
75	5.228	0.7558	0.14
80	8.713	1.0323	0.12
85	12.198	1.3088	0.11
90	15.683	1.5853	0.10
95	19.168	1.8618	0.10
100	22.653	2.1383	0.09
105	26.138	2.4148	0.09
110	29.623	2.6913	0.09
115	33.108	2.9678	0.09
120	36.593	3.2443	0.09
125	40.078	3.5208	0.09
130	43.563	3.7973	0.09
135	47.048	4.0738	0.09
140	50.533	4.3503	0.09

scan, and these values were 0.22, 0.44, 0.70 mGy at 80, 100, 120 kVp, respectively.

A very important factor to consider in selecting the machine kVp (photon energy) is how effective a given photon energy will be in revealing tissue differences. An abnormal mass of tissue that is 0.5 cm thick has an attenuation coefficient of 0.34 cm^{-1} for 80 keV photons and the fraction of photons removed is approximately $0.5 \times 0.34 = 0.17$ or about 17%. However, at 100 keV, the attenuation coefficient is 0.161 cm^{-1} and only 8% of the photons would be attenuated by the mass; therefore, the lower energy X-rays would be better for producing an image contrast in such tissue. Such results are even better for higher Z materials such as bone, and sharper contrast and image detail can be obtained if lower kVp X-rays are used to image bone versus surrounding tissues [10].

On the other hand, the higher voltage (higher energy photons) yields lower entrance doses for a given procedure, and in Tables 6 and 7, and Fig. 12 there is a clear reduction in the amount of absorbed dose in organs accompanied by reducing X-ray tube voltage from 120 kVp to 100 kVp up to more than 60%, and also we can note that at higher voltage (>90 kVp) the ratio between the absorbed dose in skin and the absorbed dose in heart approximately is constant and is less than

Table 8
Scan parameters for the comparison with Ref. [11].

Helical CT-chest	
Slice thickness	5 mm
Pitch	1.375
Tube voltage	120 kVp
Tube current	270 mA
Scan length	33–72 cm

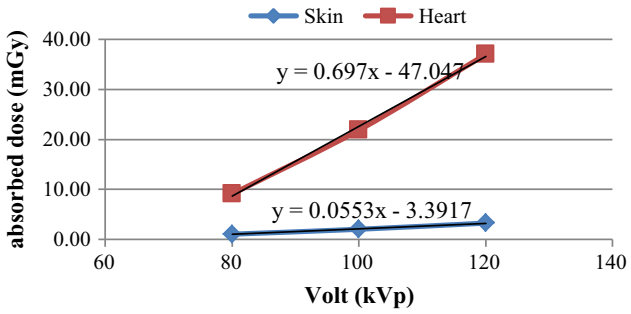

Fig. 12. Absorbed dose in heart, skin versus tube voltage.

Table 9
Calculated absorbed dose in some organs in our search and in Ref. [11].

Organ absorbed doses during CT chest scan (mGy)						
Ref. [11]					This study	
Organ	Dude[b]		Daisy[a]		Absorbed doses (mGy)	Organ
	Calculated (phantom)	Measured (Dude)	Calculated (phantom)	Measured (Daisy)		
Adrenals/Gall Bladder	3.1	3.90	3.5	4.92	3.42 3.15	Gall bladder (wall) Gall bladder (contents)
Brain	0.27	0.50	0.19	0.26	0.09	Brain
Colon	0.42	0.20	0.48	0.134	0.2 0.75 0.1 0	Ascending colon wall Transverse colon wall Descending colon all Sigmoid colon wall
Esophagus	22	20.5	16.2	12.5	7.08	Esophagus
Kidney	3.1	2.8 (each)	4.2	2.16 (each)	5.36 (both)	Kidney
Liver	14.6	14.0	13.3	11.1	8.43	Liver
Lung	38.8	22.6 (each)	26.0	10.0 (each)	12.69 13.6	Left lung Right lung
Pancreas	11.0	5.62	13.0	2.43	6.9	Pancreas
Thymus	32.0	27.2	12.1	13.1	12.49	Thymus
Thyroid	6.0	25.0	4.0	8.3	8.53	Thyroid
Uterus/Testes	0.003	0.045	0.13	0.112	0.2	Uterus/Testes
	8.2	**9.3**	**5.62**	**4**	**5.57**	Effective Dose (mSv)
	38%	**50%**	**0.89%**	**32.8%**	**–**	Diff%

[a] Daisy: the female phantom (Prins, 2011).
[b] Dude: the male phantom.

Table 10
Calculated absorbed dose in some organs in this study and in Ref. [12].

		Absorbed dose obtained from the adult male (mGy/100 mA s)					
		CT-Dose-Calc 40–70 cm			Ref. [12] 27–50 cm		
		120 kVp	100 kVp	80 kVp	120 kVp	100 kVp	80 kVp
Brain		0.07	0	0	0.1	–	–
Thyroid		1.37	0.81	0.39	6.2	5.1	2.9
Esophagus		1.55	0.9	0.44	5.4	3.4	1.5
Thymus		2.74	1.7	0.84	6.8	4.3	2
Lung[a]	Right lung	2.73	1.67	0.81	6.8	4.3	2.0
	Left lung	2.64	1.56	0.78			
Breast[a]		3.13 (both)	1.9 (both)	1.01 (both)	6.7	4.4	2.1
Heart wall	Heart (left ventricle wall)	2.3	1.36	0.64	7.1	4.6	2.1
	Heart (right ventricle wall)	2.52	1.5	0.78			
	Heart (left atrium wall)	2.16	1.26	0.56			
	Heart (right atrium wall)	2.39	1.39	0.65			
	Sum	**9.37**	**5.51**	**2.63**			
Stomach wall		0.59	0.33	0.14	3.0	2.2	0.9
Liver		0.86	0.51	0.22	3.7	2.7	1.1
Gall bladder wall		0.25	0.12	0.05	1	0.7	0.3
Adrenal[a]		1.04 (both)	0.6	0.29 (both)	1.4	1.1	0.4
Spleen		0.74	0.44	0.2	3.4	2.7	1.0
Pancreas		0.73	0.38	0.2	0.6	0.5	0.1
Kidney[a]		0.23 (both)	0.12	0.05 (both)	0.6	0.4	0.1
Small intestine wall		0.02	0	0	0.2	0.1	–
Colon wall	Ascending colon wall	0.01	0	0	0.2	0.2	–
	Transverse colon wall	0.06	0.02	0			
	Descending colon wall	0	0	0			
	Sigmoid colon wall	0	0	0			

[a] In Ref. [12] doses for sub-organs were averaged to provide a single dose with mass weighting. But in this study doses for sub-organs were summed.

1, but at lower voltage (⩽68 kVp) the ratio between the absorbed dose in skin and the absorbed dose in heart is rabidly varying and is more than 1. Hence it is always necessary to set accuracy to obtain acceptable images for medical diagnosis and to reduce patient dose to minimum value from radiation protection point.

8. The comparison

The calculated absorbed doses, during CT chest scan, were compared with previously published results. Table 8 shows the scan parameters for this study and those for the reference [11] and Table 9 contains the results of comparison. The percentage difference was calculated using the formula $diff\% = \frac{(X_{cal} - X_{ref})}{\frac{(X_{cal} + X_{ref})}{2}} \times 100$.

The results were compared also with the given values in the reference [12] for organ doses (mGy/100 mAs) obtained from the adult male hybrid phantom for chest examination for the tube potentials of 80, 100, and 120 kVp. Table 10 shows the result of comparison.

9. Conclusion

Monte Carlo method for estimating doses from CT scanning protocols was developed and tested using MIRD phantom and an assistant program to create the input file to MCNP code for each scan protocol. This program will help the user to create the MCNP input file for each scan protocol and calculate the absorbed dose components for each case.

As a result of CT chest scan using the parameters shown in Table 4, we found that the maximum absorbed dose is in heart, lungs, breasts, and thyroid respectively. For the heart muscle the total doses are 9.11, 21.86, 36.99 mGy at 80, 100, 120 kVp, respectively. In case of lungs (left + right) the total doses are 3.18, 6.45, and 10,73 at 80, 100, 120 kVp, respectively. In case of breasts the total doses are 2.03, 3.90, and 6.022 mGy at 80, 100, 120 kVp, respectively, and for thyroid 0.78,1.66, and 2.79 mGy at 80, 100, 120 kVp, respectively.

From Table 6 we can note that an increment of the tube voltage from 100 kVp to 120 kVp will increase the absorbed dose in important organs by twice, and also the ratio between the absorbed dose in skin and the absorbed dose in heart will decrease.

Therefore, it is always necessary to set accuracy to obtain acceptable images for medical diagnosis and to reduce patient dose to minimum from radiation protection point of view.

Also, a good agreement was found between the results of this study in comparison with those previously published, especially, in case of calculated Daisy phantom. On the other hand, in case of measured and calculated Dude phantom, there were significant differences due to some factors such as difference in anode angle, organs volume, and the geometry design.

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